

A potential sterile neutrino search using a two-reactor/one-detector configuration

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(Dated: March 5, 2013)

There is an observed deficit of about 6% in the expected rate of anti-neutrino interactions when averaging over many different reactor experiments. While the significance of the deficit is low (98.6 % CL), there is speculation that a non-interacting “sterile” neutrino could be the cause. In this paper we explore the possibility of a two-reactor/one-detector experiment at intermediate distances (100-500 meters) to look for a sterile neutrino in the mass range implied by this deficit. We also investigate the potential sensitivity of an existing reactor experiment (Double Chooz) which has a single Near Detector at distances of 351 m and 465 m from two reactors of identical design. We conclude that Double Chooz could investigate sterile neutrino in the Δm^2 range of 0.002 to 0.5 eV² over 5 years of near detector running.

I. INTRODUCTION

There are global hints of the possible existence of sterile neutrinos from accelerator experiments [1–4], reactor experiments [5] and cosmological measurements [6, 7]. While the existence of one or more sterile neutrinos is not the only possible explanation for these results, it nevertheless becomes interesting to devise new experiments that explore this possibility. In this paper we investigate the sensitivity of an existing experiment (Double Chooz) to detect the oscillations of electron flavor neutrinos into sterile neutrinos, and propose a new experiment optimized for this search.

There have been nearly twenty reactor neutrino experiments at distance of 10-100 meters from reactor cores. In a recent review paper [5] the expected rates were re-calculated using up-to-date reactor anti-neutrino flux predictions and a 3-flavor neutrino oscillation hypothesis. The authors found that on average there is a $\sim 6\%$ deficit in the rate of observed anti-neutrino interactions measured to that expected. This has come to be called the Reactor Anti-neutrino Anomaly (RAA), and has been taken as an indication that the 3-flavor oscillation hypothesis may not be complete. To follow up this hypothesis, the authors performed global fits using rate information from these experiments assuming a 3 active flavor neutrino and 1 sterile neutrino oscillation model (also known as a 3+1 model). Folding the results of these fits in with spectral shape constraints from the Bugey-3 experiment [8], they calculated best fit oscillation parameter values of $\Delta m_{14}^2 = 1.5$ eV² and $\sin^2(2\theta_{14}) = 0.14$ [5].

In this paper we present a new method of gaining increased sensitivity to 3+1 oscillation parameters. This method utilizes two reactors and one detector, referred to as the “two-reactor/one-detector” configuration, and relies on the differences in the measured spectrum from running each reactor singly. Thus, this method is effective only in the case of two reactor cores, each of which runs a significant period of time while the other core is down. This is indeed the case for the Chooz B reactor configuration and the Double Chooz Near Detector, now under construction. The Near Detector will be 351 m

and 465 m from two 4.25 GW_{th} power reactors. With the analysis technique described here, this configuration will lead to sensitivity in a region of Δm_{14}^2 and $\sin^2(2\theta_{14})$ that has not been previously explored.

II. SHAPE ANALYSIS OF STERILE NEUTRINOS

To help give clarity to the discussion, a simple example is described using the two-neutrino oscillation formalism. The two-neutrino survival probability can be described by the following formula:

$$\begin{aligned} P_{ee} &= 1 - \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E_{\bar{\nu}_e}}\right) \\ &= 1 - \alpha^2 \sin^2(\beta L) \end{aligned} \quad (1)$$

where $\alpha \equiv \sin(2\theta)$ and $\beta(E_{\bar{\nu}_e}) \equiv \Delta m^2/4E_{\bar{\nu}_e}$. For a single detector measuring the disappearance of $\bar{\nu}_e$ ’s from a single reactor, the sensitivity to Δm^2 and $\sin^2(2\theta)$ depends on the reactor-detector distance, L . For an appropriate, L , the visible $E_{\bar{\nu}_e}$ spectrum will be distorted due to the $L/E_{\bar{\nu}_e}$ dependence of the survival probability. It is possible to visually enhance this spectral distortion by forming a ratio using an independent $E_{\bar{\nu}_e}$ spectrum obtained at a different distance where sensitivity to Δm^2 and $\sin^2(2\theta)$ is also expected. In this paper we present a mathematical formalism for for a two-reactor/one-detector configuration. It is expected that many (but not all) detector systematics will cancel if the single-reactor running periods are roughly equally interspersed. This is discussed in more detail in section III. In addition, although the detector backgrounds are not expected to vary with reactor running period, we assume for the formalism that the relevant backgrounds have been subtracted. We note that this work was initially motivated to explain the tension between the rate measurements and spectral measurements found in the results of the Double Chooz, Daya Bay and Reno experiments in fitting for θ_{13} , which is yet not fully understood[9–12].

There are four distances (three of which are independent) that can be defined for the two-reactor/one-

detector configuration:

- (a) $L_1 \equiv$ distance from detector to reactor R_1
- (b) $L_2 \equiv$ distance from detector to reactor R_2
- (c) $L_{2-1} \equiv L_2 - L_1$
- (d) $L_{1+2} \equiv L_1 + L_2$

Using the form of equation 1, the ratio of the energy spectra obtained from the reactors R_1 and R_2 can be written as:

$$\frac{P_{ee}^{R_1}}{P_{ee}^{R_2}} = \frac{1 - \alpha^2 \sin^2(\beta L_1)}{1 - \alpha^2 \sin^2(\beta L_2)}. \quad (2)$$

This ratio can be expressed in a more useful form by multiplying the numerator and denominator by a factor of $1 + \alpha^2 \sin^2(\beta L_2)$. After simplifying, the expression in equation 2 becomes:

$$\frac{P_{ee}^{R_1}}{P_{ee}^{R_2}} = \frac{1 + \alpha^2 \sin(\beta L_{2-1}) \sin(\beta L_{1+2}) - \alpha^4 \sin^2(\beta L_1) \sin^2(\beta L_2)}{1 - \alpha^4 \sin^4(\beta L_2)} \quad (3)$$

where the spectral distortions due to the mixtures of L_1 and L_2 in sine functions are clearly revealed. The $\alpha^2 \sin(\beta L_{2-1}) \sin(\beta L_{1+2})$ creates modulations on the spectral shape at both higher and lower frequency than the modulation produced only by baseline L_1 or L_2 . In the limit that α is small, equation 3 may be expressed as:

$$\frac{P_{ee}^{R_1}}{P_{ee}^{R_2}} \approx 1 + [1 - \alpha^2 \sin^2(\beta L_2)] [\alpha^2 \sin(\beta L_{2-1}) \sin(\beta L_{1+2})] + O(6) + \dots \quad (4)$$

where the ratio is a function of the survival probability of antineutrino at a baseline of L_2 convoluted with modulations of the spectral shape at baselines L_{1-2} and L_{1+2} . In L/E space these represent different frequencies. Since reactor experiments have most of their events in the neutrino energy range of roughly 2 - 9 MeV each frequency will have a sensitive "sweet spot" in β . Of course, complication comes in with the convolution of the detector energy resolution function with the measured visible energy, which will reduce contrast in the high frequency features in the ratio spectrum. These detector effects will be covered in the next section, where we investigate the sensitivity of this technique using the Double Chooz near detector.

III. DOUBLE CHOOZ NEAR DETECTOR SENSITIVITY

The Double Chooz (DC) near detector is now being constructed at $L_1 = 351$ m and $L_2 = 465$ m from Chooz B reactors R_1 and R_2 . A five year run time for this detector (assuming a down cycle of 15% per reactor, which was the case for their most recent publication [10]) will yield 548 days of data taken with only either R_1 or R_2 on. Each reactor operates at 4.25 GW_{th}, giving expected rates of about 230 $\bar{\nu}_e$'s per day from R_1 and 130 $\bar{\nu}_e$'s per day from R_2 .

For comparison sake, the DC far detector has been currently taking data for 2 years [9, 10]. The distance between this detector and reactors (near, far) makes the technique developed in the previous section statistically limited due to the $1/L^2$ fall off of neutrino intensity. The measured rates are about 28 $\bar{\nu}_e$'s per day from R_1 and 23 $\bar{\nu}_e$'s per day from R_2 .

The DC near detector can offer sensitivity to sterile neutrinos not only by making a shape measurement at L_1 and L_2 , but also by identifying the interference terms. This is partly due to the fact that there is a frequency modulation at a distance of $L_{2-1} = 114$ m, a region which has already been probed by previous reactor experiments located at a distance of $L \sim 100$ m from the source. It is also important to note that the strength of this ratio technique with the DC near detector will not come from the sensitivity to the disappearance *rate*, but from discrimination of the neutrino oscillation spectral *shape* for values of Δm^2 less than 10^{-2} eV². This is a region that was not accessible to Bugey-3 spectral shape analysis.

The formalism developed in section II is applicable when there are no backgrounds present. In actual experiments, backgrounds such as ⁹Li and fast neutrons will have small contributions which must be taken into account. By performing a two-reactor/one-detector study of the backgrounds, complimented by the availability of reactor off data when there are only two cores, we assume a good understanding of these quantities can be obtained. In turn, these backgrounds may then be subtracted from the far and near reactor data with a small loss of sensitivity compared to statistical and detector resolution uncertainties, as the background subtraction is near fully-correlated since it is simply the same detector but a different running period.

Figure 1 shows the calculated visible energy spectra of the R_1 and R_2 reactor data for values of ($\Delta m_{14}^2 = 0.5$ eV²) without energy smearing. In the ratio analysis of the R_1 and R_2 data, the following systematic uncertainties

TABLE I. Distance from Reactor R_1 and R_2 to the center of the detector from geodesic surveys.

	L_{2-1}	L_1	L_2	L_{1+2}
Near (m)	114	351	465	816
Far (m)	117	998	1115	2113

Expected spectra after applying oscillation and core evolution

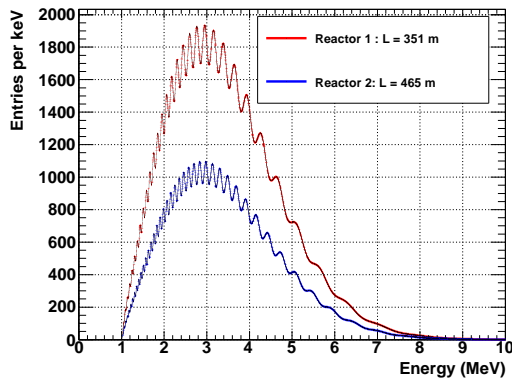


FIG. 1. Near (R_1) and far (R_2) reactor data for the DC near detector before smearing of energy resolution with $\Delta m_{new}^2 = 0.5 \text{ eV}^2$ and $\sin^2(2\theta_{new}) = 0.12$.

on the observed spectral shapes have been taken into account:

- Energy resolution: $(7 \pm 1)\%/\sqrt{E[\text{MeV}]}$ from DC far detector).
- Detector stability: estimated at 1% from the DC far detector [9] measurements of the stability of the Gd capture gamma peak.
- Reactor core size: 3.47 m diameter for the Chooz B reactors. We have assumed the neutrinos start randomly inside this core, which is a worst case assumption.
- Fuel loading: contributes $< 0.01 \%$ uncertainty, based on studies where we put in extremes of fuel loading uncertainties.

The combined effect of these uncertainties to the sensitivity of sterile neutrino oscillations are shown in Figure 2. In fact, they have very little impact on the exclusion domain of this technique with the DC near detector after 5 years of detector operation. The analysis is is clearly dominated by statistical uncertainty. The spectra from the re-evaluation of the Bugey-3 shape discrimination [5] is also included as a comparison.

IV. DISCUSSION

It should be noted that the mathematical formalism developed in section II is generic and can be applied to any two-reactor/one-detector experiment. The positive discovery of sterile neutrinos will require strong evidence and as such a strong shape discrimination and good statistics are paramount to any new proposed experiments.

There are a few guidelines required to optimize this technique for new experiments. First of all, the distances

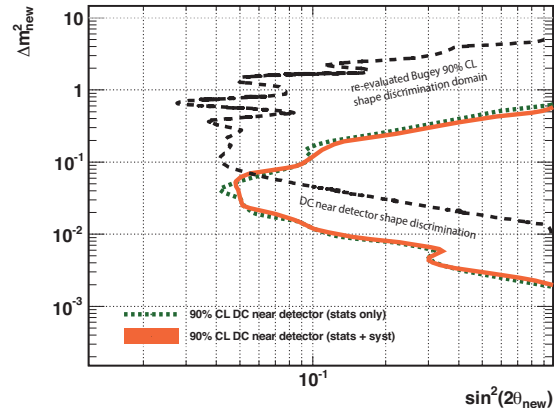


FIG. 2. Exclusion domain of Δm_{new}^2 for the case of the DC near detector. Sensitivity to sterile neutrino oscillations via spectral shape discrimination disappears for values of Δm_{new}^2 less than 0.008 eV^2 and greater than 0.16 eV^2 at $\sin^2(2\theta_{new}) = 0.12$ at 90% CL.

between the detector and the far and near reactors cannot be equal since the interference term would vanish. When taking the ratio of two spectra, the strength of shape discrimination is correlated with the difference of baseline (L_{2-1}) and the addition of the baseline (L_{2+1}). One can envision an experiment with $L_{2-1} = 10 \sim 15 \text{ m}$ that can be devised such that the ILL region can be probed, however, the reactor core size will add greater uncertainty at short distances and will have to be modeled carefully.

New experiments must also seek to improve spectral shape sensitivity. The principle culprit for the loss of shape discrimination power is the energy resolution of a detector. Ratio analyses for different values of Δm_{14}^2 are shown with no smearing applied in Figure 3 and with smearing applied in Figure 4. If sensitivity to larger Δm_{14}^2 is desired, detectors with better energy resolution is a vital requirement.

Currently, there are few experiments which have sensitivity to Δm_{new}^2 below the limits set by Bugey-3. The ICARUS experiment can claim sensitivity in this region, however it is a $\nu_\mu \rightarrow \nu_e$ appearance experiment and will not address the probability of $\bar{\nu}_e$ disappearance. If a solution to the RAA exists in the form of sterile neutrino oscillations, such a solution could be probed by reactor $\bar{\nu}_e$ experiments which cleverly address the many unknowns present in reactor $\bar{\nu}_e$ flux predictions. In addition, some cosmological studies (e.g. those using WMAP-9 data) are more consistent with 4 rather than 3 flavors of neutrinos ($N_{eff} = 3.84 \pm 0.40$) [7]. When combined with BAO and H_0 data and other CMB measurements, this same study gives an upper limit on the total mass of neutrinos of $m_{tot} < 0.44 \text{ eV}$ at 95% CL. If all of this mass were due to a sterile flavor, then the region below $(0.44)^2 \sim 0.19 \text{ eV}^2$ becomes even more interesting to explore with this new technique.

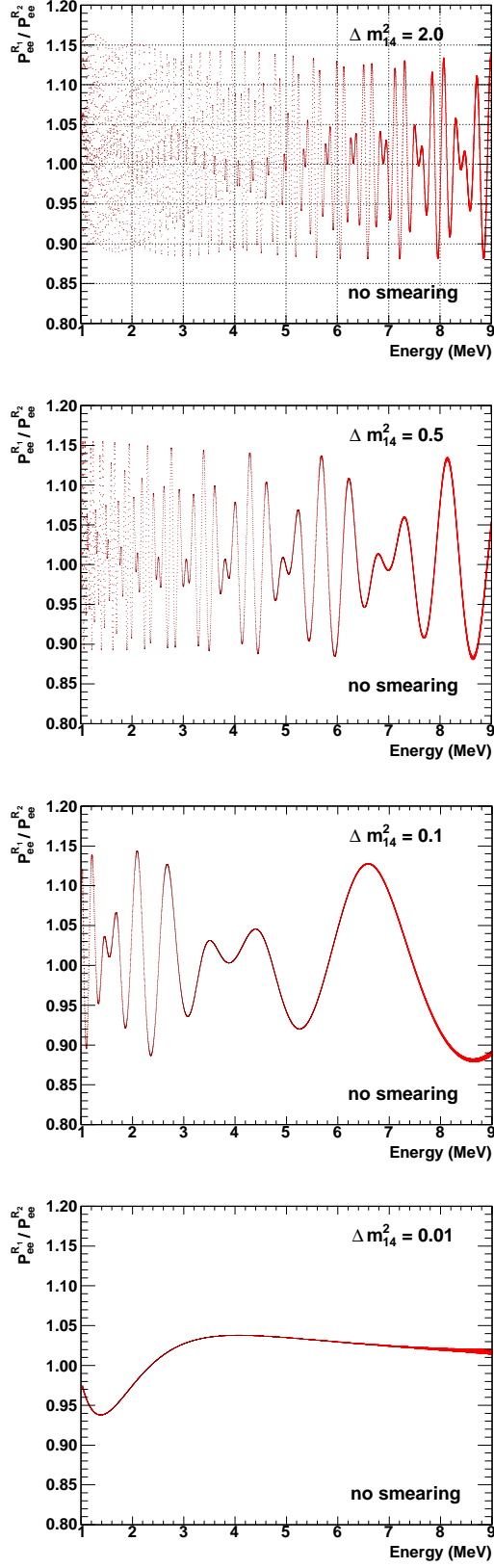


FIG. 3. Ratio analysis for value of Δm_{14}^2 respectively of 2.0, 0.5, 0.1 and 0.01 eV^2 with no detector smearing. Larger values of Δm_{14}^2 lead to higher frequency of oscillation.

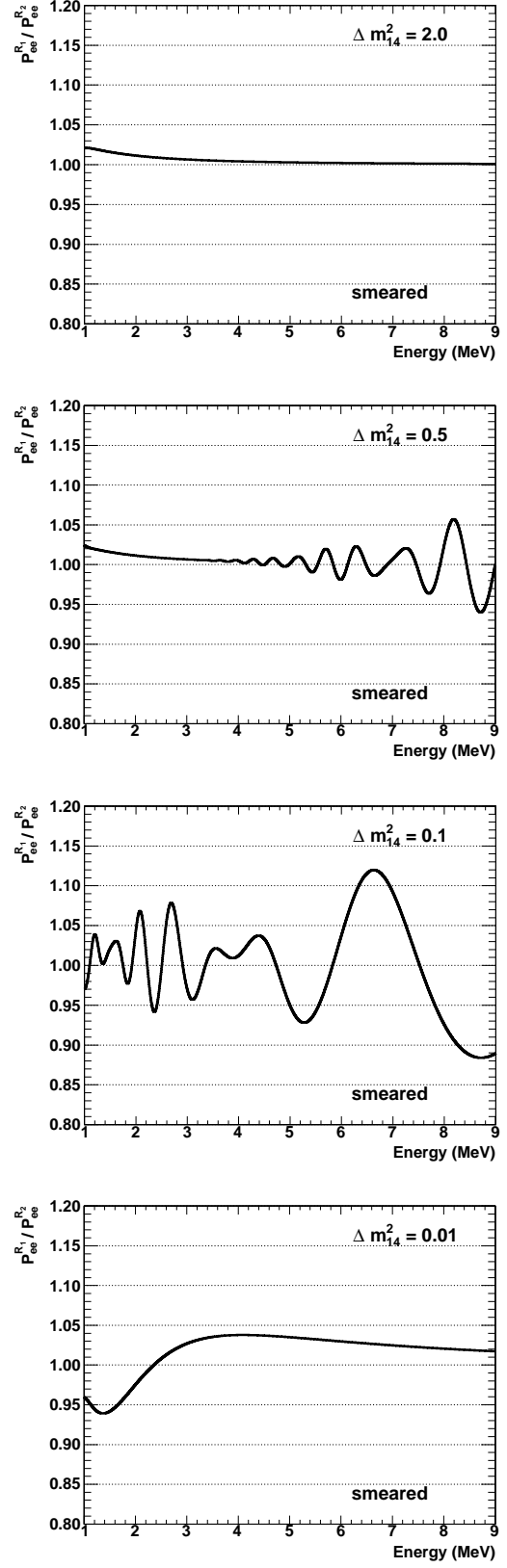


FIG. 4. Effect of detector resolution on the ratio analysis for value of Δm_{14}^2 respectively of 2.0, 0.5, 0.1 and 0.01 eV^2 with a $7\%/\sqrt{E[\text{MeV}]}$ detector smearing. High frequency features are washed out by the smearing of the detector resolution.

V. CONCLUSION

The technique presented in this paper provides a formalism that could be used to explore possible sterile neutrino explanation tension that the reactor anti-neutrino experiment such as Double Chooz, RENO and Daya Bay are observing. A positive discovery would imply that sterile neutrinos have a mass less than 0.2 eV^2 , which is consistent with current cosmological results. It is ob-

served that the distances between the Chooz B reactors and the DC near detector will allow sensitivity to a new region of Δm_{14}^2 from 0.002 to 0.5 eV^2 . The near DC detector will provide high statistics and will have the power to discriminate spectral features due to active flavors from those due to sterile neutrinos. Future experiments could seek to optimize the distances involved in a two-reactor/one-detector analysis to increase spectral shape discrimination in the Δm^2 region of interest.

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